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A brief review on experimental film cooling

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Abstract: Film cooling is employed for effective cooling in nozzles and combustion chambers using a spray of coolant fluid in the mainstream flow to cool the body. Experimental analysis was performed elaborately in the past years to get an exact analysis of film cooling effectiveness with different parameters. The current work outlines the entire experimental work done to expand the available knowledge on film cooling and its techniques. The paper discusses in detail the work done on gaseous and liquid film cooling and the research performed to date on flat plate cooling as well. The paper also outlines in brief the studies done on the mechanism of entrainment and film cooling. Studies performed to analyze the influence of various parameters such as blowing ratio, measurement flux ratio, density ratio, flow structure, hole geometry, surface roughness and boundary layer displacement thickness are also outlined in this paper. This paper thus outlines the entire experimental work performed on film cooling applied to flat plates to date.

Keywords: Film Cooling, Experimental Studies, Gaseous Film Cooling.

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1. Introduction: In the past years, a large amount of experimental, analytical and numerical investigations have been done to measure the film cooling performance. A brief review of the past experimentations on the film cooling has been highlighted in this paper. Film Cooling is basically the introduction of an auxiliary liquid (coolant or injected liquid) at one or more distinct areas along a surface accessible to very high temperature environment to ensure protection in the downstream region as well as in the injection region. The invention of film cooling is often attributed to K. Wieghardt [1] a German scientist who applied this technique to de-icing of aircraft wings by blowing warm air over them. Research for film cooling of turbine components started in the late 1950s with the introduction of air-cooled turbines around 1960. Initially only internal cooling was applied. Film cooled blades were found in service from the late 60s, first in military engines and later also in commercial flight. Film cooling of stationary gas turbines was applied only much later. Film cooling research conducted in the 1950's and 1960's can be roughly divided into gas and liquid film cooling experiments.

2. Gaseous Film Cooling Studies: Among most initial studies, Goldstein [2] utilized a 35 º inclined axial shaped hole with a primarily round cross-section area extended to every side by 10. A significant increment in the effectiveness was accounted for by him. Numerous studies are accessible for film coolant estimations over a flat plate surface with a streamwise angle infusion of 35 º and with compound angle infusion. They all reported that compound angle infusion gave better lateral spreading and coverage and blending of mainstream flow with coolant jets. Sen et al. [3] examined the impact of three diverse compound angles of a circular shaped hole and reported that the forward expansion holes with compound angle has amplified lateral spreading and mixing along with the heat transfer coefficient which as a result increased the momentum flux. According to Ekkad et al. [4], high turbulence intensity accounted for compound angle holes affects FCE. They observed that for normal injection, FCE was higher for higher density coolant while for large compound angle injection; even lower density coolant provides higher effectiveness values. Lee et al.'s [5] experimental studies indicated enhanced effectiveness at higher blowing ratios for different shaped holes with compound angle. On the other hand, the existence of hot cross flow absorption into the film hole at the hole exit plane was witnessed for large orientation angles.

Experimental analysis for a single row of diffuser holes with compound edge infusion was conducted by Dittmar et al [6]. A solid influence of the cooling air cross flow has been detected for all blowing ratios. Their outcomes demonstrated that the fan shaped hole with a certain compound angle gave the most elevated FCE values at high blowing ratios contrasted with other hole shapes. Jurban et al. [7] likewise demonstrated similar trending results from their experiments for two staggered rows of holes with compound angle. Maiteh et al. [8] demonstrated that the increment in the free stream turbulence intensity and the existence of ideal pressure gradients in the flow may decrease the FCE for compound angle holes. Hung et al. [9] undertook a detailed study that assessed the film cooling execution on curved walls with compound angle configuration. The estimations demonstrated that for concave surfaces, higher heat transfer stages induced by large flow disturbance of compound infusion lead to poor global film cooling execution particularly at high blowing ratios. Compound angle injection on convex surface demonstrated high FCE at adequate and high blowing proportions. Michel et al. [10] conducted experimental as well as numerical study on a cooling film dispensing from a multi-perforated wall of a simplified combustor. They demonstrated that the film thickness and turbulence are significantly enhanced by compound angles of holes. Cho et al. [11] explored the impacts of compound angle of a solitary cone shaped hole with orientation angles of 0º, 45º and 90º. They concluded that for successful surface protection, it's better to choose compound angle injection over the axial one. Bell et al. [12] carried out experimental study on the forward and laterally diffused holes with compound angle injections. It was witnessed that the best way to ensure protection over the broadest range of blowing ratios, momentum flux ratios and steamwise area, it is better to use laterally diffused holes with compound angle injection followed by a forward diffused compound angle injection rather than with cylindrical hole without compound angle. The FCE downstream of a row of compound angle cylindrical and diffused holes were explored by Taslim et al. [13]. The outcomes demonstrated that the diffuser hole provides best possible surface protection over a wide range of blowing ratios and also for higher blowing ratios.

3. Liquid Film Cooling Studies: Earlier, very few experimental investigations were accompanied by researchers in the field of liquid film cooling in rocket ignition combustion chambers. Liquid film cooling investigations at low chamber pressure, below 150 psia, were conducted. Kinney et al. [14] conducted experiments with hot air traveling through 2- and 4-in diameter tubes that were liquid film cooled with water, water/detergent solutions, and aqueous ethylene glycol. Aside from the coolant types, hot core gas temperature, chamber pressure and coolant to hot gas mass flow rate ratios were varied to determine the corresponding liquid film cooled length for various injectors. They discovered a non-linear relationship between coolant flow rate and the liquid-cooled length. Their measured cooling effectiveness decreased with increasing coolant flow rate and a correlation was developed which predicted the minimum coolant flow rate. Kinney et al.'s [14] model involved heavy empiricism and the units of the empirical constants in the correlation are disregarded. Knuth's [15] investigated liquid "film stability" and its effects on mass transfer due to evaporation and un-vaporized liquid droplet entrainment from the film surface to the core gas flow. Water, aqueous sucrose solution, aqueous zinc chloride solution, and carbon tetrachloride were used as coolants. Similarly, the varying test parameters included hot core gas temperature and chamber pressure. Emmons [16] did one of the few experimental liquid film cooling investigation at relatively high chamber pressure (up to 780 psia). An empirical dimensionless parameter, the coefficient of heat transfer between liquid film and hot core gas was determined from an extensive test matrix. Test parameters include different hot core gas (hydrogen or air), hot core gas temperature, and chamber pressure. The effects of different coolants (water, aqueous ammonia solution, ethyl- alcohol, or Freon-113) on coolant requirements were also examined. Gater and L'Ecuyer [17] extended these results further and discovered that mass transfer occurred due to the entrainment of un-vaporized liquid droplets can exceed mass transfer due to evaporation from the film surface. The entrainment was postulated to shear off from the crest of the wave-like disturbances on the liquid film and is dependent on the roughness of the liquid film surface. A porous injector was employed with water, methanol, butanol, or hydrocarbon fuel, RP-1 in Gater's [17] experimental investigations. Due to the designed experimental setup, the liquid coolant flow rate was deemed inaccurate and hence resulted in incorrect mass transfer observed. Fewer studies integrated the film cooling test results with a methodical analytical procedure for predicting the adiabatic wall temperature given known quantities in a LRE. Yu [18] integrated Grissom's [19] and Stechman's [20] models for predicting the wall temperature of sub-critical water cooled H_2O_2 rocket with mixed results. Following Yu's work, Haberlen [21] modified Grissom's model and applied the gaseous film cooling entrainment model of Rousar and Ewen [22] to a RP-1/GOX staged combustion LRE.

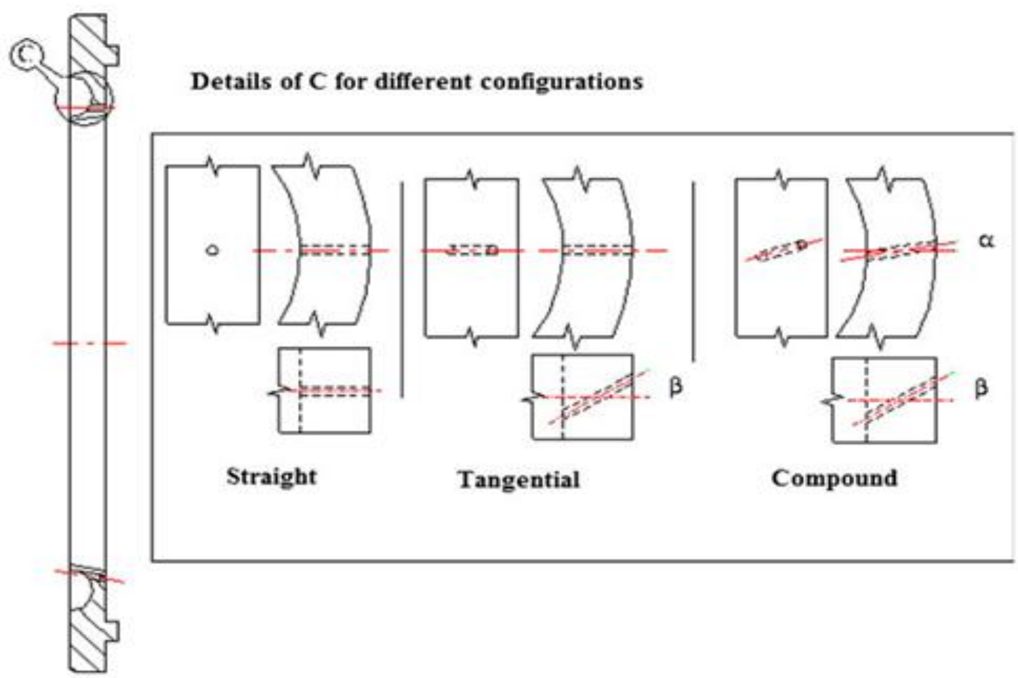

Figure 1: Coolant injector configuration

Kinney [14] utilized permeable and impinging jet sort of injectors with angular holes cut at 25 º to the axis. No significant distinction was achieved in the outcomes with the two diverse coolant injectors. Abramson [23] utilized annular slots slanted at 30 º to the nozzle in his interior film cooling analyses of the liquid ammonia-liquid oxygen rocket engine. Film cooling of the whole nozzle was accomplished with film coolants, for example, water and anhydrous ammonia. Knuth [15] directed trials with radial injectors and determined the sufficient conditions which are required for the stability of the thin liquid wall flows which were flowing under the effect of velocity turbulence gas. Boden [24] conducted the very first experimental study at JPL on film cooling. They utilized nine injector configurations out of which seven were situated in the radial heading and two were drilled at 70 º off the radial direction. A deflector plate was utilized to inject the coolant axially before entering the motor. The obtained data has been checked and correlated by Welsh [25]. It was detected that injection from a solitary area in the combustion chamber was the minimum efficient method and injection of coolant in a whirling design negligibly affected cooling, although the effectiveness of the coolant was increased after the addition of a deflector plate. Morrell [26] had effectively achieved liquid film cooling studies experimentally with a vertical rectangular slot and tangential type injectors with slots at 45º to the axis. Tangential slot injections (Figure 1) were unsuccessful to enhance the cooling effectiveness and thus utilized just for a couple of runs. Warner [27] utilized radially injected coolant holes through circumferential slots which were inscribed in the combustion chamber of the rocket motor using hydrogen as fuel. He found that the amount of coolant required to film cool a given length of surface was successfully decreased by using dual slot injections in contrast with that required when a single hole is in employment. The relevance of film cooling to rocket motors utilizing earth-storable, space-storable and cryogenic fuel mixtures were examined by Stechman et al. [28]. In all the experimentations, fuel was utilized as the coolant and was found to have significant improvement in the zone of cooling properties. The studies demonstrated that N_2O_4/MMH, ClF_5/MMH and other comparable charge blends are promptly versatile to small scale film cooled rocket motors. The coolant was injected using the circumferential cooling holes of the injector, which were coordinated at different chamber impingement angles keeping in mind the end goal to guarantee complete exposure of the walls. The subtle elements of the injector configurations were not accessible and couldn't make any perilous assessments. Kesselring et al. [29] carried out experiments with tangential injectors in a nickel calorimeter chamber. Based on the calculations of normally expected heat flux without transpiration they assumed that the film is instantly dissipated. The study utilized distinctive configurations of simple angle and compound angle holes for gaseous coolant. An azimuthal angle of 10º was given to all the compound angled holes. One arrangement of holes had an angle of 30º tangentially, and another had a tangential angle of 45º. Two arrangements of injector holes were utilized for the coolant. One arrangement of holes had an angle of 30º tangentially, while the other arrangement had an angle of 30º tangentially and an azimuthal angle of 10º combined. FCE, the uniformity of film and wall adherence have been compared using nitrogen gas and water as coolants through a progression of thorough experimentations. Comparison for the same injector design has been done for both liquid and gaseous coolant performances.

3. Research on Flat Plate Film Cooling: Since quite a while now, research on flat plate film cooling has been done subsequently. Goldstein [2] concentrated on the film cooling effectiveness of a circular tube slanted at 35 degrees to the mainstream. The comparison of simple to compound angle injection and shaped hole injection was done by Sen and Schmidt et al. [3]. Even after getting the results from heat transfer coefficient and effectiveness, the earlier data was extremely sparse. Ekkad et al. [4] gave point by point surface heat transfer estimations utilizing the transient liquid crystal technique. Similarly, there have been various studies on shaped holes. Sen and Schmidt et al. [3] worked on the simple to compound angle to shaped hole injection and concluded that the forward expanded holes gave considerably greater lateral film coverage than the other cases. Gritsch et al. [30, 31] exhibited about the film cooling effectiveness and discharge coefficients for three different hole geometries. They investigated fan-shaped and laidback fan-shaped holes to cylindrical holes with no angle. From their outcomes, they demonstrated that laidback fan-shaped holes gave higher laterally averaged FCE because of enhanced spreading of coolant jets. Sargison et al. [32] contemplated a converging slot hole geometry in which the hole moves from circular to slot with merging in the axial direction and separation laterally. The endeavor was to make the 3-D nature of the jet into a 2-D slot film. The outcomes were meant for enhancing effectiveness. Lemmon et al. [33] demonstrated that the arrangement of these counter rotating vortices is directed by the shear layer between the mainstream and coolant jet and not because of the viscous wall influence in the cooling hole or plenum. Dittmar et al. displayed an evaluation of different film cooling hole designs in a replicated turbine surface experiment. They showed that differently shaped holes with some compound angles deliver the best successful cooling in contrast with other geometries. Lu et al. [34] presented a crescent shaped hole geometry and contrasted it to the conventional cylindrical hole and converging slot hole geometries. They demonstrated that the crescent hole performed well at all blowing ratios creating an effectiveness of around 0.7-0.9 inside of 3-5 hole diameters downstream and high effectiveness estimations of 0.4 at X/D~15. The converging slot hole exit geometry was likewise viable and almost alike to the crescent shaped hole geometry. A large portion of the above studies with different shaped holes concentrated mainly on decreasing the upward momentum of coolant jets by increasing the exit area of hole or by changing the holes to slots.

4. Studies on the Mechanism of Entrainment and Film Stability: In literature very few studies are available which describes the mechanism of film entrainment and the stability of liquid film cooling that are applicable to combustion chambers and turbine blades. Kinney **[14]** mentioned regarding the visual objective facts of liquid film streams on the interior surface of the tubes comprising mainstream air. Water, water-detergent solutions, and aqueous ethylene glycol solutions were used as film coolants and air was used as the core gas. When the coolant mass flow rate was beyond the critical value, he detected turbulences at the liquid-gas crossing point triggering loss of coolant. This value was found to vary with liquid viscosity and surface tension, and did not show any change with air stream Reynolds number. Knuth **[15]** from his liquid film investigations affirmed that longer wavelength instabilities influences acted only for some critical flow rates of coolant. Small aggravations with wavelength of the order of ten film thickness were seen at all flow rates. However, some liquid drops were found entraining by the gas stream from the peaks of long wave length disturbances. Gater et al. **[17]** piloted investigations with a flat film and measured the quantity of liquid that stayed close to the wall with a knife edge capture slot. Gater perceived that the instabilities at the liquid gas interface were reliant on the momentum fluxes which were contrary to the perceptions by Kinney and Knuth. He suggested that the amount of liquid entrained was a component of momentum flux of the gas and surface tension of the fluid film. However, it may be noted that Gater's experiments were at lower gas mass flux conditions and using heated air, whereas Knuth's observations were based on cold flow experiments. Adechy and Issa **[35]** introduced the Eulerian-Lagrangian approach, in which an Eulerian methodology was utilized for the gas phase while Lagrangian outline was used for the tracing of all the liquid droplets. An experimental correlation was used to model the entrainment process. Coy et al. **[36]** led studies on entrainment consider slot injectors with Mach number of around 0.6 at the test section. According to him, a critical flow rate exists of the coolant film after which the further injected liquid will get entrained into the gas phase. Yu et al. **[37]** have examined the advantages of whirling the liquid film to decrease entrainment and to provide sensible thermal wall situations at a lower performance. Raymond & Louis **[38]** studied the effect of normal, slanted and compound injection for different blowing ratios. They observed that in the case of slanted in-line hole configuration, the film was separated from the surface and penetrated into the free-stream at blowing ratio greater than 0.5. However for compound angle injection, the film is attached to the surface for even higher blowing ratio. Film cooling effectiveness for film hole configuration with opposite orientation angles was evaluated by Joon Ahn et al. **[39]** The effects of blowing ratio on boundary layer temperature distributions were investigated with thermochronic liquid crystal technique. The study inferred that for the blowing ratio of 0.5, the injectant is focused close to the surface irrespective of the arrangement to give elevated values of adiabatic film cooling effectiveness in the near hole areas, however more protection was provided in the further downstream region through high blowing ratios. Hassan Nasir et al. **[40]** further explored the impact of discrete shaped tabs with various angles of injection on the film cooling from an array of cylindrical holes. Three tab orientations were examined and observations were done in a low-speed wind tunnel utilizing the transcend liquid crystal technique. Results demonstrate that the tabs situated downwards give the most astounding effectiveness at a blowing ratio of 0.56 while the tabs situated on a level plane gives most astounding film effectiveness values at blowing ratios of 1.13 and 1.7.

5. Literature Based on Effect of Various Parameters:

5.1 Temperature Measurement: R. J. Goldstein et al. **[2]** in a progression of trials have utilized the temperature method to give information on the film cooling effectiveness, with a truncated low speed wind tunnel and thermocouples to quantify the wall temperatures. Kim et al. [41] have also used a low speed wind tunnel to provide effectiveness data, which they obtain via the heat transfer coefficient. They had two wind tunnels- one, of rather small cross section, measuring 2" x 0.5"; the other, more realistically, measuring 16 " x 6 ". Lander and Fish [42] utilized a combustion chamber to provide a hot mainstream for a cascade of blades, where they measured the effectiveness on a blade under steady state conditions. Finally, the temperature method was used by Nicolas and Le Meur [43], but they also did some concentration measurements to compare with their 'temperature' results and found good agreement between the two methods.

Liess [44] have also carried out tests to provide data at higher Mach numbers using the temperature technique. Smith et al. [45] employed a shock tunnel to provide the high speed, high pressure and temperature mainstream to approximate to the conditions in a gas turbine. Here, of course, the flow was of short duration and utilized thin film heat transfer devices to quantify the heat transfer rates from which the film cooling Effectiveness was deduced. Most of these experimenters have also measured the ratio of the heat transfer coefficients with and without secondary flow. All, except Goldstein et al. [2] who used a steady state system, used a method which relied upon the measuring of the transient heating or cooling response of a test surface, from which the heat transfer coefficient could be calculated.

5.2 Concentration Measurement: Fewer experimenters have used the foreign gas technique. Rastogi and Whitelaw [46] used air, with helium as a tracer gas, as the injectant and also mixtures of Freon 12 and air in a series of wind tunnel tests in 1972. Freon12 and air with a helium tracer were, also injected into a wind tunnel mainstream by Brocq et al. [47] and by Launder et al. [48], the latter using carbon dioxide as a third injectant. The density of Freon 12 is 4.26 times the density of air, while carbon dioxide density is 1.54 times that of air.

5.3 Effect of Flow Structure: A study of the fluid mechanics associated with a jet issuing into a main stream was made by Andreopoulus and Rodi [49]. Triple hot wire probes were used to measure all three velocity components. Once emerged, the jet was bent over abruptly by the cross stream and two longitudinal counter rotating vortices formed, causing the jet cross section to appear kidney shaped. The highest turbulence and shear stress levels occurred at locations from two to four diameters downstream of the hole, and were coincident with the maximum mean velocity gradients. Pietrzyk et al. [50] did velocity measurements with LDA in high density ratio film cooling environments. They showed that the largest region of high turbulence is coincident with shear layers on the upwind side of the leaving jet and directly above the wake region that forms behind the jet.

5.4 Influence of Blowing and Momentum Flux Ratios: Wilfert and Fottner [51] did measurements on the suction side in a turbine blade cascade. They state that at low blowing proportions a cooling jet acts somewhat alike a usual obstacle and the blending for the most part happens in the boundary layer. With expanding blowing proportion the jet enters more profound into the mainstream. They detected not only the kidney vortex pair but also the individual horseshoe vortex around each jet and found that its position is intensely reliant on the blowing ratio and effects the aerodynamic mixing.

Pederson et al. [52] showed in a comprehensive study in the late 70s of film cooling wall effectiveness that the velocity ratio between jet and main flow is relevant to the film effectiveness achieved. As the velocity ratio increases the film cooling wall effectiveness increases to a maximum, and then rapidly decreases. This maximum occurs around 0.5 and indicates that for higher values of the velocity ratio the jet separates from the wall, allowing the mainstream to flow underneath. The effectiveness is low directly downstream of the hole for conditions where the jet has separated from the wall. Later works discarded of the velocity ratio as descriptive parameter and used mainly blowing and momentum flux ratio. Yuen et al. [53] showed in their experiment with a single round hole on a flat plate that the highest film cooling effectiveness in the near hole region is achieved with a blowing ratio smaller than 0.5, whereas for areas downstream of the region, the most extreme effectiveness at the blowing ratio of 0.5 and a momentum flux ratio of zero. This is attributed to the required additional momentum to transport the jet further downstream. They also demonstrated that the blowing ratio had little impact on heat transfer with the exception of the prompt and close field regions, where the heat transfer improved by around 25% as the blowing ratio was amplified from 0.33 to 2.

5.5 Influence of Density Ratio: Camci **[54]** did experiments on the suction side of a film cooled turbine blade in a short duration facility. He showed that an increase in density ratio while keeping the blowing ratio constant lowered the heat transfer coefficient. This effect was found to be more pronounced for high blowing ratios. Goldstein et al. **[55]** did experiments on a flat plate with a single array of film cooling holes to investigate the effect of the density ratio. They expressed that the utilization of a generally denser coolant, as is found in numerous applications, requires an essentially higher blowing ratio to bring jet detachment from the surface than when the density ratio is at unity. These findings suggest that the momentum flux ratio is a more appropriate parameter to describe film cooling than blowing ratio.

5.6 Influence of Hole Geometry and Shape: Gritsch et al. **[30, 31]** concentrated on point by point estimations of the flat plate cooling effectiveness and coefficient of heat transfer downstream of a solitary film cooling hole. They reported that in contrast to the cylindrical hole, the other two expanded holes viz. fan-shaped and laidback fan-shaped, indicate altogether enhanced protection of the surface downstream of the injection, especially at high blowing proportions. Teng et al. **[56]** contemplated the influence of various hole shapes on the film cooling of a turbine blade unsteady wake flow conditions. They utilized the same unsteady wake model simulation facility as Du et al. **[57].** They found that the heat transfer coefficients for both fan-shaped and laidback fan-shaped holes were much lower directly after the hole exit rather than in the cylindrical holes. Hence it can be concluded that the fan-shaped holes provide better film cooling effectiveness over laidback fan-shaped holes and therefore vastly improved film cooling effectiveness than cylindrical holes. Yuen et al. **[58]** performed estimations on flat plate with different blowing ratios and streamwise injection angles. They reasoned that even a small injection angle results in a higher film cooling effectiveness and an escalated heat transfer coefficient. The effect on both parameters however, was found to be moderate.

5.7 Influence of Surface Roughness: The heat transfer coefficient and the film cooling effectiveness get significantly affected by the surface finishing. In 1986, Goldstein et al. **[55]** reported that at low blowing ratios, the surface roughness decreases the film cooling effectiveness by 20 %; however, it increases by 50 % at high blowing ratios. Bogard **[59]** found that the surface roughness had a significant effect on film cooling by studying different cases of hole geometry: a round hole with 30° inclination angle, a 60° angle away from the main stream in the lateral direction, and a 15° forward expansion with an orientation angle of 60°. Barlow and Kim **[60]** found that for a small level of roughness the film cooling effectiveness was lower than for higher surface roughness. Additionally, the film cooling effectiveness was corrupted farther downstream and enhanced the heat transfer coefficient by 50 % for rougher surfaces (Schmidt et al., 1996, **[3]**). In a real case, a gas turbine airfoil operates under several environments with high temperature and stress, and the airfoil has clear-off roughness. There are many causes for increasing airfoil surface roughness and they depend on the processes, which create the rough surface. Airfoil surface roughness can be created from fuel deposits, LE erosion and deposits, hot corrosion and erosion, pitting, and mild and large spallation (Bons et al. **[61]**). They measured the roughness for the end-wall to be 28 μm. They stated that the roughness level was 4 to 8 times greater than the levels for a production line airfoil, which is less than 1 μm. Moreover, the erosion grooves close to the film hole have a significant effect on the film cooling effectiveness. Cardwell et al. **[62]** investigated the effect of a mid-passage gap and roughness on the end-wall film cooling using a large-scale turbine vane. They noted that adiabatic film cooling effectiveness decreased by increasing the surface roughness at high blowing ratios; although at low blowing ratios there was no significant effect from surface roughness.

5.8 Effect of Boundary Layer Displacement Thickness: Only two researchers have considered the effect of the boundary layer thickness: Goldstein et al. **[55]** and Liess **[44]**. In general, they found that an increase in the boundary layer displacement thickness tended to reduce the effectiveness, this being most marked close to the injection holes, and at low blowing parameters. The effect is explained by suggesting that, with a thinner boundary layer, the jets travels shorter distance of low momentum flow before being deflected. Liess' **[44]** results show a much greater variation in effectiveness with boundary layer displacement thickness, than do those of Goldstein et al.; also they show the effect to extend over a distance of 50 diameters downstream. Goldstein et al. **[55]** show the effect to have almost disappeared on the centreline within 30 diameters. These discrepancies highlight the fact that both Goldstein et al. and Liess vary the ratio of the boundary layer displacement thickness to hole diameter, utilizing diverse hole sizes, and by varying the mainstream velocity the latter having the effect of altering both the boundary layer thickness and the Reynolds number. In one case Goldstein et al varied the boundary layer thickness directly, by moving the boundary layer tripwire. However, the overall result is that it is impossible to determine the extent of the effectiveness variation, which is due to the change in boundary layer thickness alone.

5.9 Effect of Pressure Gradient: Liess **[44]** is also one of the three researchers to consider the effect of pressure gradients on film cooling; the others are Nicolas & Le Meur **[43]** and Launder and York **[48]**. Lander and Fish **[42]** have measured the film cooling effectiveness in the presence of pressure gradients, but have no results without the pressure gradients to compare these with. Liess found that a contour which was placed in the roof segment of the working section in his modified wind tunnel, giving a favorable pressure gradient, produced a fall in effectiveness far downstream of the injection holes. Liess suggests that this was probably due to increased mixing, but it is difficult to make any quantitative statement, as the pressure gradients only extended between 0 and 15 and 0 and 25 diameters downstream. These results are at variance with those of Launder and York, who used a flat, angled plate in the roof of their working section which, they found, improved the effectiveness behind the first row of holes in their multiple row injection plate by 25%. The experimenters point out that the blowing rate will vary down the injection plate, due to the change in static pressure along it. This had been partly eliminated by increasing the pressure drop through the delivery system, but any variation would result in lower blowing rates from the first row and, thus, a higher effectiveness. The angled plate employed by the experimenters stretched from some considerable distance upstream of the injection holes to over 40 diameters downstream. This must therefore have produced varying boundary layer thicknesses over the first row of holes, depending upon the level of mainstream acceleration which would, in turn, have produced variations ineffectiveness regardless of the pressure gradient. Nicolas and Le Meur conducted a series of experiments in which they used both curved and straight ducts, with and without contours, to produce the pressure gradients. They found that a negative pressure gradient on a flat plate tended to maintain the cooling film further downstream, and that cooling via holes with the pressure gradient was as good as cooling via a slot. When comparing a concave surface with a constant pressure flat plate, the authors found an improvement of up to 60% at a blowing rate of unity. Improvements over the flat plate situation were also noticed on the convex side of the working section, but they were not so marked. No values for the boundary layer thicknesses were given, so again it is difficult to ascribe the variations to any particular effect. Hartnett et al. **[63]**, in tests on a slot arrangement, found little difference between the levels of effectiveness produced by favorable pressure gradients starting at the point of injection, and those produced without a pressure gradient. There, the boundary layer displacement thickness was similar for all cases considered. Zakkay et al. **[64]** suggested that an adverse pressure gradient should improve the film cooling effectiveness at high Mach numbers with sonic tangential injection.

6. Discussion and Conclusions: Many experimental and computational studies have been done to investigate the film cooling process with the objective of understanding this complex flow and heat process, and to devise the best possible cooling schemes for high effectiveness. Hole geometries are important because they can affect the film cooling performance. Laterally and forward expanded holes provide higher values of averaged effectiveness and lower values of averaged heat transfer coefficients than round holes. Moreover, the advanced film cooling holes reduce jet lift-off hence increasing the film-cooling performance and reducing the heat transfer coefficient over the target surface and downstream of the film holes. There is no significant effect of the number of film hole rows on the heat transfer coefficient at low blowing ratios, however, at high blowing ratios, the heat transfer coefficient increases with increasing number of film rows.

At low blowing ratios, the film cooling performance for the majority of film holes is almost the same, but expanded exit holes yield higher performance compared to round holes. For high blowing ratios, the coolant jet undergoes lift-off, therefore, the interaction between the two streams increases, hence causing a reduction in film cooling effectiveness. A decrease in density ratio causes an increase in the downstream heat transfer coefficient on the film-cooled surface for inclined hole angles less than 90°, however no significant effect on heat transfer coefficient for 90° inclined holes (normal injection) was observed. Reducing the density ratio has the same effect as increasing the momentum flux ratio. It reduces the lateral spreading of the jet, thus lowering the spanwise averaged adiabatic film cooling effectiveness. Moreover, the density ratio provides a high heat transfer coefficient while producing higher turbulence eddies at the jet hole.

Large mainstream length scale enhances the turbulence mixing and carets a strong vortex, which increases with increasing blowing ratios, thereby the heat transfer coefficient increases. The span-wise adiabatic film cooling effectiveness is increased at low main stream turbulence and blowing ratios, however film cooling effectiveness increases at high blowing ratios by increasing the main stream turbulence intensity. Presence of Pressure gradient hardly improves the effectiveness of film cooling. Surface finishing has a significant effect on both the film cooling effectiveness, and the heat transfer coefficient. At low blowing ratios, the surface roughness decreases the film cooling effectiveness by 20 %; however, it increases by 50 % at high blowing ratios.

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